

Finite temperature calculations for the spin polarized asymmetric nuclear matter with the LOCV method

M. Bigdeli^{1,3*}, G.H. Bordbar^{2,3†} and A. Poostforush²

¹*Department of Physics, Zanzan University,*

P.O. Box 45195-313, Zanzan, Iran[‡]

²*Department of Physics, Shiraz University, Shiraz 71454, Iran[§]*

³*Research Institute for Astronomy and Astrophysics of Maragha,*

P.O. Box 55134-441, Maragha, Iran

Abstract

The lowest order constrained variational (LOCV) technique has been used to investigate some of the thermodynamic properties of spin polarized hot asymmetric nuclear matter, such as the free energy, symmetry energy, susceptibility and equation of state. We have shown that the symmetry energy of the nuclear matter is substantially sensitive to the value of spin polarization. Our calculations show that the equation of state of the polarized hot asymmetric nuclear matter is stiffer for the higher values of the polarization as well as the isospin asymmetry parameter. Our results for the free energy and susceptibility show that the spontaneous ferromagnetic phase transition cannot occur for hot asymmetric matter.

* E-mail: m_bigdeli@znu.ac.ir

† E-mail: ghbordbar@shirazu.ac.ir

‡ Permanent address

§ Permanent address

I. INTRODUCTION

The possible occurrence of the spontaneous phase transition to a ferromagnetic state in nucleonic matter is very important for studies relevant to astrophysical problems, such as the physical origin of the magnetic field of the pulsars [1–4]. The study of the thermodynamic and magnetic properties of spin polarized hot asymmetric nuclear matter, such as free energy, symmetry energy, magnetic susceptibility plays a crucial role in understanding the ferromagnetic phase transition, the equation of state and the structure of systems as diverse as the neutron rich nuclei and protoneutron stars.

A protoneutron star (newborn neutron star) is born within a short time just after the supernovae collapse. In this stage, the interior temperature of the neutron star matter is in the order of 20-50 MeV [5]. Determination of the dependence of the symmetry energy on the spin polarization and the behavior of the magnetic susceptibility versus the density are of special interests in description of the occurrence of the ferromagnetic phase transition in asymmetric nuclear matter. In addition these quantities are useful to estimate the mean free path of the neutrino in the dense nucleonic matter which is a relevant information for understanding the mechanism of the supernova explosion and the cooling process of the neutron stars [6].

There may exist several possibilities for the generation of the magnetic field in a neutron star. Among them are the conservation of the magnetic flux of the original star, a kind of dynamo mechanism, phase transition to a ferromagnetic state, or a combination of above mechanisms. The possibility of the existence of a phase transition to a ferromagnetic state in the neutron matter and nuclear matter has been studied by several authors [7-32], without any general agreement. In most calculations, the neutron star matter is approximated by pure neutron matter, at zero temperature. Some calculations such as those based on the hard sphere gas model [7, 8], Skyrmelike interactions [21], variational calculation using the Reid soft-core potential [14] and relativistic Dirac-Hartree-Fock approximation with an effective nucleon-meson Lagrangian [19], show that the neutron matter becomes ferromagnetic at some densities. There are other calculations such as Monte Carlo [23] and Brueckner-Hartree-Fock calculations [24–27] using modern two-body and three-body realistic interactions, which show no indication of ferromagnetic transition at any density for the neutron matter and asymmetric nuclear matter. Properties of the polarized neutron matter

at finite temperature have been studied by several authors [30–32]. Bombaci et al. [32] have studied these properties within the framework of the Brueckner-Hartree-Fock formalism using the AV_{18} nucleon-nucleon interaction. Their results show no indication of a ferromagnetic transition at any density and temperature. Lopez-Val et al. [31] have used the D1 and D1P parameterization of the Gogny interaction and the results of their calculation show two different behaviors. Whereas the D1P force exhibits a ferromagnetic transition at a density of $\rho \sim 1.31 fm^{-3}$ whose onset increases with temperature, no sign of such a transition is found for D1 at any densities and temperatures. Rios et al. [30] have used Skyrme-like interactions and their results indicate the occurrence of a ferromagnetic phase of the neutron matter. The influence of the finite temperature on the antiferromagnetic (AFM) spin ordering in the symmetric nuclear matter with the effective Gogny interaction, within the framework of a Fermi liquid formalism, has been studied by Isayev [33, 34]. Here in our article, we use the lowest order constrained variational (LOCV) formalism to investigate the possibility of the transition to a ferromagnetic phase for the polarized hot asymmetric nuclear matter.

The LOCV method has been developed to study the bulk properties of the quantal fluids [35–37]. This technique has been used for studying the ground state properties of the finite nuclei and treatment of isobars [38–40]. Modarres has extended the LOCV method to the finite temperature calculations and has applied it to the neutron matter, nuclear matter and asymmetric nuclear matter in order to calculate the different thermodynamic properties of these systems [41–44]. A few years ago, we calculated the properties of nuclear matter at zero and finite temperatures using the LOCV method with the new nucleon-nucleon potentials [45–47]. Recently we have computed the properties of the spin polarized neutron matter [48], the spin polarized symmetric [49] and asymmetric nuclear matters and neutron star matter [50] at zero temperature. In these works the microscopic calculations employing the LOCV method with the realistic nucleon-nucleon potentials have been used. We have concluded that the spontaneous phase transition to the ferromagnetic state does not occur. We have also calculated the thermodynamic properties of the spin polarized neutron matter [51] and symmetric nuclear matter [52] such as the free energy, magnetic susceptibility, entropy and pressure using the LOCV method at finite temperature. Our calculations do not show any transition to a ferromagnetic phase for hot neutron matter and hot symmetric nuclear matter.

In the present work, we want to calculate the properties of spin polarized asymmetric

nuclear matter with the LOCV technique at finite temperature employing the AV_{18} potential [53].

II. LOCV CALCULATION OF THE SPIN POLARIZED HOT ASYMMETRIC NUCLEAR MATTER

Spin polarized asymmetric nuclear matter is an infinite system composed of spin-up and spin-down neutrons with densities $\rho_n^{(+)}$ and $\rho_n^{(-)}$, respectively, and spin-up and spin-down protons with densities $\rho_p^{(+)}$ and $\rho_p^{(-)}$, respectively. The total densities for neutrons (ρ_n) and protons (ρ_p) are given by:

$$\rho_p = \rho_p^{(+)} + \rho_p^{(-)}, \quad \rho_n = \rho_n^{(+)} + \rho_n^{(-)}, \quad (1)$$

and the total density of the system is

$$\rho = \rho_p + \rho_n. \quad (2)$$

Labels (+) and (-) are used for spin-up and spin-down nucleons, respectively. One can use the following parameter to identify a given spin polarized state of the asymmetric nuclear matter,

$$\delta_p = \frac{\rho_p^{+} - \rho_p^{-}}{\rho_p}, \quad \delta_n = \frac{\rho_n^{+} - \rho_n^{-}}{\rho_n} \quad (3)$$

δ_p and δ_n are proton and neutron spin asymmetry parameters, respectively. These parameters can have values in the range of 0.0 (unpolarized) to 1.0 (fully polarized). The asymmetry parameter which describes the isospin asymmetry of the system is defined as,

$$\beta = \frac{\rho_n - \rho_p}{\rho}. \quad (4)$$

Pure neutron matter is totally asymmetric nuclear matter with $\beta = 1$ and the symmetric nuclear matter has $\beta = 0$.

To obtain the macroscopic properties of this system, we should calculate the total free energy per nucleon, $F = E - \mathcal{T}S$, where \mathcal{T} is the temperature, and E and S are the total energy and entropy per nucleon, respectively. In the case of spin polarized asymmetric nuclear matter, the free energy per particle can be calculated by a parabolic approximation

resulted from the charge independence and time-reversal invariance of the nucleon-nucleon interaction as follows [25],

$$F(\rho, \mathcal{T}, \beta, \delta_n, \delta_p) = F_{snucm}(\rho, \mathcal{T}, \beta = 0, \delta_n = 0, \delta_p = 0) + F_1(\rho, \mathcal{T})\left(\frac{1+\beta}{2}\delta_n + \frac{1-\beta}{2}\delta_p\right)^2 + F_2(\rho, \mathcal{T})\beta^2 + F_3(\rho, \mathcal{T})\left(\frac{1+\beta}{2}\delta_n - \frac{1-\beta}{2}\delta_p\right)^2, \quad (5)$$

where the coefficients $F_1(\rho, \mathcal{T})$, $F_2(\rho, \mathcal{T})$ and $F_3(\rho, \mathcal{T})$ have been determined in the following way,

$$\begin{aligned} F_1(\rho, \mathcal{T}) &= F(\rho, \mathcal{T}, \beta = 0, \delta_n = 1, \delta_p = 1) - F_{snucm}(\rho, \mathcal{T}, \beta = 0, \delta_n = 0, \delta_p = 0), \\ F_2(\rho, \mathcal{T}) &= F(\rho, \mathcal{T}, \beta = 1, \delta_n = 0, \delta_p = 0) - F_{snucm}(\rho, \mathcal{T}, \beta = 0, \delta_n = 0, \delta_p = 0), \\ F_3(\rho, \mathcal{T}) &= F(\rho, \mathcal{T}, \beta = 1, \delta_n = 1, \delta_p = 1) - F_{snucm}(\rho, \mathcal{T}, \beta = 0, \delta_n = 0, \delta_p = 0) \\ &\quad - F_1(\rho, \mathcal{T}) - F_2(\rho, \mathcal{T}). \end{aligned} \quad (6)$$

We calculate the total energy per nucleon (E) using LOCV method as follows [51, 52]. We adopt a trial many-body wave function of the form

$$\psi = \mathcal{F}\phi, \quad (7)$$

where ϕ is the uncorrelated ground state wave function of A independent nucleons (simply the Slater determinant of the plane waves) and $\mathcal{F} = \mathcal{F}(1 \cdots A)$ is an appropriate A -body correlation operator which can be replaced by a Jastrow form i.e.,

$$\mathcal{F} = \mathcal{S} \prod_{i>j} f(ij), \quad (8)$$

in which \mathcal{S} is a symmetrizing operator. Now, we consider the cluster expansion of the energy functional up to the two-body term [9],

$$E([f]) = \frac{1}{A} \frac{\langle \psi | H \psi \rangle}{\langle \psi | \psi \rangle} = E_1 + E_2. \quad (9)$$

For the polarized hot asymmetric nuclear matter, the one-body term E_1 is

$$E_1 = \sum_{j=p,n} \sum_{i=+,-} E_{1j}^{(i)}, \quad (10)$$

where $E_{1j}^{(i)}$ is the one-body energy of nucleon j with spin projection i ,

$$E_{1j}^{(i)} = \sum_k \frac{\hbar^2 k^2}{2m} n_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)}). \quad (11)$$

$n_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)})$ is the Fermi-Dirac distribution function,

$$n_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)}) = \left(e^{\beta [\epsilon_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)}) - \mu_j^{(i)}(\mathcal{T}, \rho_j^{(i)})]} + 1 \right)^{-1}. \quad (12)$$

In the above equation $\beta = \frac{1}{k_B \mathcal{T}}$, $\mu_j^{(i)}$ is the chemical potential of nucleon j with spin projection i which is determined at any values of the temperature (\mathcal{T}), number density ($\rho_j^{(i)}$) and polarization (δ_j) by applying the following constraint,

$$\sum_k n_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)}) = A_j^{(i)}, \quad (13)$$

and $\epsilon_j^{(i)}$ is the single particle energy of nucleon j with spin projection i . In our formalism, the single particle energy of nucleon j with momentum k and spin projection i is written approximately in terms of the effective mass as follows [30, 31, 34]

$$\epsilon_j^{(i)}(k, \mathcal{T}, \rho_j^{(i)}) = \frac{\hbar^2 k^2}{2m_j^{*(i)}(\rho, \mathcal{T})} + U_j^{(i)}(\mathcal{T}, \rho_j^{(i)}). \quad (14)$$

$U_j^{(i)}(\mathcal{T}, \rho_j^{(i)})$ is the momentum independent single particle potential. In fact, we use a quadratic approximation for single particle potential incorporated in the single particle energy as a momentum independent effective mass and introduce the effective masses, $m_j^{*(i)}$, as variational parameters [51, 54]. We minimize the free energy with respect to the variations in the effective masses and then obtain the chemical potentials and the effective masses of the spin-up and spin-down nucleons at the minimum point of the free energy. This minimization is done numerically.

The two-body energy E_2 is

$$E_2 = \frac{1}{2A} \sum_{ij} \langle ij | \nu(12) | ij - ji \rangle, \quad (15)$$

where

$$\nu(12) = -\frac{\hbar^2}{2m} [f(12), [\nabla_{12}^2, f(12)]] + f(12)V(12)f(12). \quad (16)$$

In above equation, $f(12)$ and $V(12)$ are the two-body correlation and potential. In our calculations, we use the AV_{18} two-body potential which has the following form [53],

$$V(12) = \sum_{p=1}^{18} V^{(p)}(r_{12}) O_{12}^{(p)}, \quad (17)$$

where

$$\begin{aligned}
O_{12}^{(p=1-18)} = & 1, \sigma_1 \cdot \sigma_2, \tau_1 \cdot \tau_2, (\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2), S_{12}, S_{12}(\tau_1 \cdot \tau_2), \\
& \mathbf{L} \cdot \mathbf{S}, \mathbf{L} \cdot \mathbf{S}(\tau_1 \cdot \tau_2), \mathbf{L}^2, \mathbf{L}^2(\sigma_1 \cdot \sigma_2), \mathbf{L}^2(\tau_1 \cdot \tau_2), \\
& \mathbf{L}^2(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2), (\mathbf{L} \cdot \mathbf{S})^2, (\mathbf{L} \cdot \mathbf{S})^2(\tau_1 \cdot \tau_2), \\
& \mathbf{T}_{12}, (\sigma_1 \cdot \sigma_2)\mathbf{T}_{12}, S_{12}\mathbf{T}_{12}, (\tau_{\mathbf{z}1} + \tau_{\mathbf{z}2}).
\end{aligned} \tag{18}$$

In above equation, $S_{12} = [3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \cdot \sigma_2]$ is the tensor operator and $\mathbf{T}_{12} = [3(\tau_1 \cdot \hat{r})(\tau_2 \cdot \hat{r}) - \tau_1 \cdot \tau_2]$ is the isotensor operator [53]. In the LOCV formalism, the two-body correlation $f(12)$ is considered to have the following form [37],

$$f(12) = \sum_{k=1}^3 f^{(k)}(r_{12})P_{12}^{(k)}, \tag{19}$$

where

$$\begin{aligned}
P_{12}^{(k=1-3)} = & \left(\frac{1}{4} - \frac{1}{4}O_{12}^{(2)} \right), \left(\frac{1}{2} + \frac{1}{6}O_{12}^{(2)} + \frac{1}{6}O_{12}^{(5)} \right), \\
& \left(\frac{1}{4} + \frac{1}{12}O_{12}^{(2)} - \frac{1}{6}O_{12}^{(5)} \right).
\end{aligned} \tag{20}$$

The operators $O_{12}^{(2)}$ and $O_{12}^{(5)}$ are given in Eq. (18).

In our formalism, we minimize the two-body energy E_2 with respect to the variations in the correlation functions $f_\alpha^{(k)}$ subject to the normalization constraint [37, 46],

$$\frac{1}{A} \sum_{ij} \langle ij | h_{S_z}^2 - f^2(12) | ij \rangle_a = 0. \tag{21}$$

In the case of polarized nuclear matter, the Pauli function $h_{S_z}(r)$ is as follows

$$h_{S_z}(r) = \begin{cases} \left[1 - \frac{1}{\nu} \left(\frac{\gamma^{(i)}(r)}{\rho} \right)^2 \right]^{-1/2} & ; S_z = \pm 1 \\ 1 & ; S_z = 0 \end{cases} \tag{22}$$

where

$$\gamma^{(i)}(r) = \frac{2\nu}{(2\pi)^2} \int n^{(i)}(k, \mathcal{T}, \rho^{(i)}) J_0(kr) k^2 dk. \tag{23}$$

Here ν is the degeneracy of the system. From the minimization of the two-body cluster energy, we get a set of coupled and uncoupled differential equations the same as presented in Ref. [52]. We can obtain the correlation functions by solving these differential equations and then calculate the two-body energy. Finally, we can compute the energy and the free energy of the system.

III. RESULTS AND DISCUSSION

Fig. 1 shows the free energy per nucleon of the spin polarized hot asymmetric nuclear matter versus the total number density (ρ) for different values of neutron polarization (δ_n), proton polarization (δ_p) and isospin asymmetry parameter (β) at $\mathcal{T} = 10$ and 20 MeV . It can be seen from this figure that at each temperature for a given value of isospin asymmetry parameter, the free energy of polarized hot asymmetric nuclear matter increases by increasing the polarization. For all temperatures and isospin asymmetry parameters, we do not see any crossing between the free energy curves of different polarizations. The difference between the free energies of different polarizations increases by increasing the density. Therefore, we can conclude that there is no spontaneous transition to the ferromagnetic phase for the hot asymmetric nuclear matter. Fig. 1 also shows that for a given polarization and temperature, the free energy increases by increasing the isospin asymmetry parameter. From Fig. 1, we see that the free energy of spin polarized asymmetric nuclear matter decreases by increasing the temperature. We have found that only for the lower values of temperature (\mathcal{T}), neutron polarization (δ_n), proton polarization (δ_p) and isospin asymmetry parameter (β), the free energy curve shows a minimum point. However, at higher values of these quantities, this minimum point disappears showing no bound state for spin polarized hot asymmetric nuclear matter.

For the unpolarized case of nuclear matter with $\beta = 0.0$ (symmetric nuclear matter), we have compared the free energies at different temperatures in Fig. 2. It is seen that the free energy of unpolarized symmetric nuclear matter decreases by increasing the temperature, especially at low densities. From Fig. 2, we can see that at zero temperature, the saturation density (density of minimum point of energy) for the unpolarized symmetric nuclear matter is about $\rho = 0.31 \text{ fm}^{-3}$ which is greater than the empirical value (0.16 fm^{-3}). Our results also show that at $\mathcal{T} = 0 \text{ MeV}$, the energy of symmetric nuclear matter at our calculated saturation density (binding energy) is about -18 MeV which is smaller than the empirical value (-16 MeV).

For the polarized hot asymmetric nuclear matter, the nuclear symmetry energy is given by

$$F_{sym}(\rho, \mathcal{T}, \delta_n, \delta_p) = F(\rho, \mathcal{T}, \beta = 1, \delta_n, \delta_p) - F(\rho, \mathcal{T}, \beta = 0, \delta_n, \delta_p). \quad (24)$$

In Fig. 3, we have plotted the nuclear symmetry energy (F_{sym}) of spin polarized hot asym-

metric nuclear matter as a function of the temperature at $\rho = 0.31$ and 0.16 fm^{-3} for two cases with $\delta_n = \delta_p = 0.0$ and $\delta_n = \delta_p = 1.0$. It is seen that at low temperatures, for a given polarization, the difference between the symmetry energies of different densities is substantially large. However, this difference decreases as the temperature increases. Fig. 3 shows that for each density, the symmetry energy increases by increasing the polarization and temperature. However, for each density, the difference between the symmetry energies of different polarization decreases by increasing the temperature. From Fig. 3, for the case of unpolarized nuclear matter ($\delta_n = \delta_p = 0$), at $\mathcal{T} = 0 \text{ MeV}$, we have found that the value of the symmetry energy corresponding to our calculated saturation density ($\rho = 0.31 \text{ fm}^{-3}$) is about 39 MeV . For this case of nuclear matter, the empirical value of the nuclear symmetry energy is $28 - 32 \text{ MeV}$ corresponding to the empirical saturation density of about $\rho = 0.16 \text{ fm}^{-3}$ [57]. This shows that our calculated symmetry energy as well as our saturation density are greater than the empirical results. We have also found that the symmetry energy of the unpolarized nuclear matter at $\mathcal{T} = 0 \text{ MeV}$ for $\rho = 0.16 \text{ fm}^{-3}$ is about 26 MeV , which is less than its empirical value. The density dependence of the nuclear symmetry energy of polarized hot asymmetric nuclear matter has been also shown in Fig. 4. For each value of the polarization, we see that F_{sym} is an increasing function of the density. However, the rate of increasing of the symmetry energy versus the density increases by increasing the polarization.

The response of a system to the magnetic field is characterized by the magnetic susceptibility, χ , which in the case of asymmetric nuclear matter is defined by a 2×2 matrix as follows,

$$1/\chi = \begin{pmatrix} 1/\chi_{nn} & 1/\chi_{np} \\ 1/\chi_{pn} & 1/\chi_{pp} \end{pmatrix}, \quad (25)$$

where the matrix elements $1/\chi_{ij}$ are given by,

$$1/\chi_{ij} = \frac{\rho}{\mu_i \rho_i \mu_j \rho_j} \left(\frac{\partial^2 F}{\partial \delta_i \partial \delta_j} \right)_{\delta_i = \delta_j = 0}. \quad (26)$$

In the above equation, ρ is the total density, μ_i (μ_j) and ρ_i (ρ_j) are the magnetic moment and density of the particle i (j), respectively, and δ_i and δ_j are the spin asymmetry parameters of particles i and j , respectively. The onset of the spin instability of the system appears when

the sign of the determinant of this matrix becomes negative. We calculate the magnetic susceptibility of the polarized asymmetric nuclear matter in terms of the ratio $\frac{\det(1/\chi)}{\det(1/\chi_F)}$, where χ_F is the magnetic susceptibility for an ideal Fermi gas containing noninteracting protons and neutrons. For the polarized hot asymmetric nuclear matter, the ratio $\frac{\det(1/\chi)}{\det(1/\chi_F)}$ versus the temperature, for $\rho = 0.16 \text{ fm}^{-3}$ at different values of the isospin asymmetry parameter (β) has been presented in Fig. 5. This figure shows that for all values of the isospin asymmetry parameter and temperature, $\frac{\det(1/\chi)}{\det(1/\chi_F)}$ is positive. This behavior indicates that there is no magnetic instability for the hot asymmetric nuclear matter. From Fig. 5, we see that for all isospin asymmetry parameters, the ratio $\frac{\det(1/\chi)}{\det(1/\chi_F)}$ which is greater than unity, monotonically decreases by increasing the temperature. This shows that as the temperature increases, the strong correlation in nucleonic matter which arises by nucleon-nucleon interaction, becomes less important. Fig. 5 also shows that for all given temperatures, the ratio $\frac{\det(1/\chi)}{\det(1/\chi_F)}$ increases by decreasing the asymmetry parameter (β). This indicates that the proton fraction substantially affects the magnetic susceptibility of asymmetric nuclear matter. This effect has been already pointed out by Kutschera et al. [58] and Bernardos et al. [20]. In Fig. 6, we have plotted the ratio $\frac{\det(1/\chi)}{\det(1/\chi_F)}$ as a function of the density at $\mathcal{T} = 20 \text{ MeV}$ for a wide range of the isospin asymmetry parameters. We see that for all densities, this ratio is always positive, indicating that the spontaneous ferromagnetic phase transition does not occur for hot asymmetric nuclear matter at any densities. Fig. 6 also shows that this ratio is always greater than unity and always increases by increasing the density. Therefore, we can conclude that the strong nucleon-nucleon correlation becomes more important as the density of system increases.

The equation of state of the polarized hot asymmetric nuclear matter for different values of the polarization and isospin asymmetry parameter at $\mathcal{T} = 10$ and 20 MeV has been presented in Fig. 7. We see that for all temperatures and isospin asymmetry parameters, the equation of state becomes stiffer as the polarization increases. We also see that for a given polarization at each temperature, the pressure of spin polarized hot asymmetric nuclear matter increases by increasing the isospin asymmetry parameter. By comparing the two panels of Fig. 7, we can see that increasing the temperature leads to the stiffer equation of state for spin polarized asymmetric nuclear matter.

IV. SUMMARY AND CONCLUSIONS

We have used the lowest order constrained variational (LOCV) method to calculate the free energy of the polarized hot asymmetric nuclear matter at different temperatures, for various values of the isospin asymmetry parameter and spin polarization employing the AV_{18} two-nucleon potential. Our results show that the free energy of this system increases by increasing both the isospin asymmetry parameter and the spin polarization while it decreases by increasing the temperature. We have also calculated the symmetry energy of this system to show that this term depends on the spin polarization, temperature and density. The magnetic susceptibility of spin polarized hot asymmetric nuclear matter has been also calculated for a wide range of densities and isospin asymmetry parameters at different temperatures. Our calculations do not show any spontaneous phase transition to the ferromagnetic state. We have also computed the pressure of spin polarized hot asymmetric nuclear matter for different values of the polarization, isospin asymmetry parameter and temperature. Our results show that for all temperatures and densities, the equation of state of this system is an increasing function of spin polarization and the isospin asymmetry parameter. Finally, an agreement is seen between our results and those of other many-body calculations.

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- [1] S. Shapiro and S. Teukolsky, *Black Holes, White Dwarfs and Neutron Stars*, (Wiley-New York, 1983).
 - [2] F. Pacini, *Nature (London)* **216** (1967) 567.
 - [3] T. Gold, *Nature (London)* **218** (1968) 731.
 - [4] J. Navarro, E. S. Hernandez and D. Vautherin, *Phys. Rev. C* **60** (1999) 045801.
 - [5] A. Burrows and J. M. Lattimer, *Astrophys. J.* **307** (1968) 178.
 - [6] N. Iwamoto and C. J. Pethick *Phys. Rev. D* **25** (1982) 313.
 - [7] D. H. Brownell and J. Callaway, *Nuovo Cimento* **B 60** (1969) 169.

- [8] M. J. Rice, Phys. Lett. **A 29** (1969) 637.
- [9] J. W. Clark and N. C. Chao, Lettere Nuovo Cimento **2** (1969) 185.
- [10] J. W. Clark, Phys. Rev. Lett. **23** (1969) 1463.
- [11] S. D. Silverstein, Phys. Rev. Lett. **23** (1969) 139.
- [12] E. Østgaard, Nucl. Phys. **A 154** (1970) 202.
- [13] J. M. Pearson and G. Saunier, Phys. Rev. Lett. **24** (1970) 325.
- [14] V. R. Pandharipande, V. K. Garde and J. K. Srivastava, Phys. Lett. **B 38** (1972) 485.
- [15] S. O. Backman and C. G. Kallman, Phys. Lett. **B 43** (1973) 263.
- [16] P. Haensel, Phys. Rev. **C 11** (1975) 1822.
- [17] A. D. Jackson, E. Krotscheck, D. E. Meltzer and R. A. Smith, Nucl. Phys. **A 386** (1982) 125.
- [18] M. Kutschera and W. Wojcik, Phys. Lett. **B 223** (1989) 11.
- [19] S. Marcos, R. Niembro, M. L. Quelle and J. Navarro, Phys. Lett. **B 271** (1991) 277.
- [20] P. Bernardos, S. Marcos, R. Niembro and M. L. Quelle, Phys. Lett. **B 356** (1995) 175.
- [21] A. Vidaurre, J. Navarro and J. Bernabeu, Astron. Astrophys. **35** (1984) 361.
- [22] M. Kutschera and W. Wojcik, Phys. Lett. **B 325** (1994) 271.
- [23] S. Fantoni, A. Sarsa and K. E. Schmidt, Phys. Rev. Lett. **87** (2001) 181101.
- [24] I. Vidana, A. Polls and A. Ramos, Phys. Rev. **C 65** (2002) 035804.
- [25] I. Vidana and I. Bombaci, Phys. Rev. **C 66** (2002) 045801.
- [26] W. Zuo, U. Lombardo and C.W. Shen, in Quark-Gluon Plasma and Heavy Ion Collisions, Ed. W.M. Alberico, M. Nardi and M.P. Lombardo, World Scientific, p. 192 (2002).
- [27] W. Zuo, U. Lombardo and C. W. Shen, nucl-th/0204056.
W. Zuo, C. W. Shen and U. Lombardo, Phys. Rev. **C 67** (2003) 037301.
- [28] A. A. Isayev and J. Yang, Phys. Rev. **C 69** (2004) 025801.
- [29] A. Akmal, V. R. Pandharipande and D. G. Ravenhall, Phys. Rev. **C 58** (1998) 1804.
- [30] A.Rios, A. Polls and I. Vidana, Phys. Rev. **C 71**(2005) 055802.
- [31] D. Lopez-Val, A.Rios, A. Polls and I. Vidana, Phys. Rev. **C 74** (2006) 068801.
- [32] I. Bombaci, A. Polls, A. Ramos, A.Rios and I. Vidana, Phys. Lett. **B 632** (2006) 638.
- [33] A. A. Isayev, Phys. Rev. **C 72** (2005) 014313.
- [34] A. A. Isayev, Phys. Rev. **C 76** (2007) 047305. **B 632** (2006) 638.
- [35] J. C. Owen, R. F. Bishop and J. M. Irvine, Ann. Phys., N.Y., **102**, 170 (1976).
- [36] J. C. Owen, R. F. Bishop and J. M. Irvine, Nucl. Phys. **A 274**, 108 (1976).

- [37] J. C. Owen, R. F. Bishop and J. M. Irvine, Nucl. Phys. **A 277**, 45 (1977).
- [38] R. F. Bishop, C. Howes, J. M. Irvine and M. Modarres, J. Phys. G: Nucl. Phys. **4**, 1709 (1978).
- [39] M. Modarres and J. M. Irvine , J. Phys. G: Nucl. Phys. **5**, 7 (1979).
- [40] M. Modarres and J. M. Irvine , J. Phys. G: Nucl. Phys. **5**, 511 (1979).
- [41] M. Modarres, J. Phys. G: Nucl. Phys. **19**, 1349 (1993).
- [42] M. Modarres, J. Phys. G: Nucl. Phys. **21**, 351 (1995).
- [43] M. Modarres, J. Phys. G: Nucl. Phys. **23**, 923 (1997).
- [44] H. R. Moshfegh and M. Modarres, J. Phys. G: Nucl. Phys. **24**, 821 (1998).
- [45] G. H. Bordbar and M. Modarres, J. Phys. G: Nucl. Phys. **23**, 1631 (1997).
- [46] G. H. Bordbar and M. Modarres, Phys. Rev. **C 57**, 714 (1998).
- [47] M. Modarres and G. H. Bordbar, Phys. Rev. **C 58**, 2781 (1998).
- [48] G. H. Bordbar and M. Bigdeli, Phys. Rev. **C 75** (2007) 045804.
- [49] G. H. Bordbar and M. Bigdeli, Phys. Rev. **C 76** (2007) 035803.
- [50] G. H. Bordbar and M. Bigdeli, Phys. Rev. **C 77** (2008) 015805.
- [51] G. H. Bordbar and M. Bigdeli, Phys. Rev. **C 78** (2008) 054315.
- [52] M. Bigdeli, G. H. Bordbar and Z. Rezaei Phys. Rev. **C 80** (2009) 034310.
- [53] R. B. Wiringa, V. Stoks and R. Schiavilla, Phys. Rev. **C 75** (1995) 38.
- [54] B. Friedman and V.R. Pandharipande, Nucl. Phys. **A 361** (1981) 502.
- [55] I. Bombaci and U. Lombardo, Phys. Rev. **C 44** (1991) 1892.
- [56] B. A. Li, Phys. Rev. **C 69** (2004) 064602.
- [57] P. E. Haustein, At. Data Nucl. Data Tables **39** (1988) 185.
- [58] M. Kutschera and W. Wojcik, Phys. Lett. **B 223** (1989) 11.

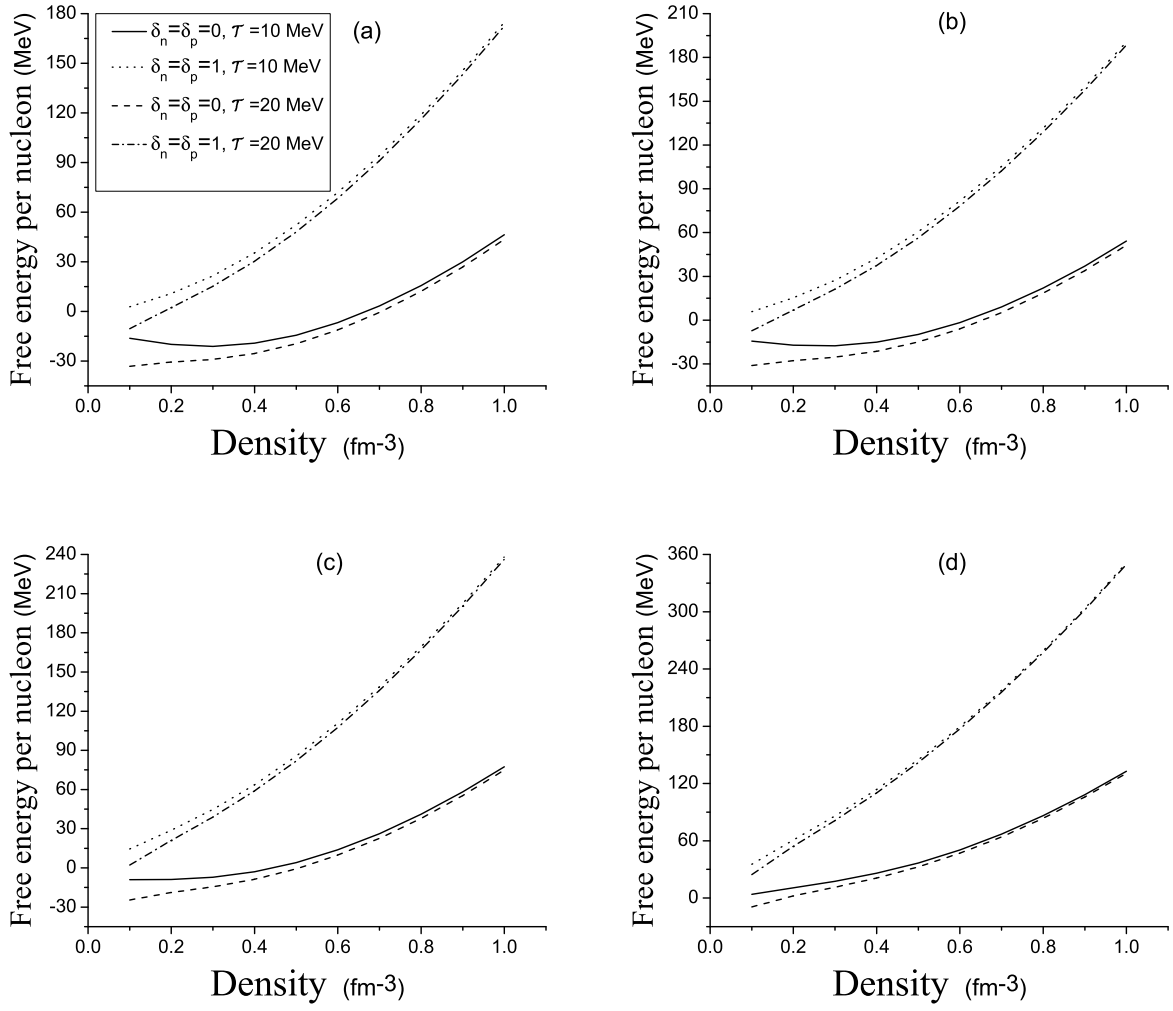


FIG. 1: The free energy per nucleon of spin polarized hot asymmetric nuclear matter as a function of the total number density (ρ) for unpolarized and fully polarized matter at $\mathcal{T} = 10$ and 20 MeV for $\beta = 0.0$ (a), 0.3 (b), 0.6 (c) and 1.0 (d).

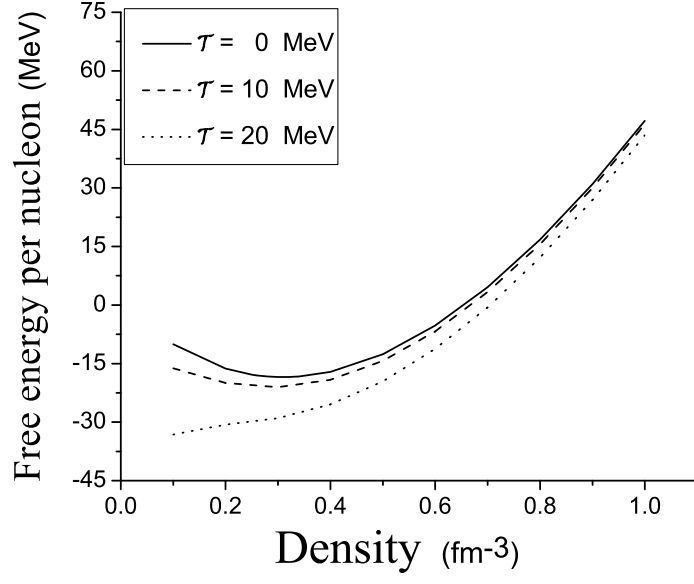


FIG. 2: The free energy per nucleon of the unpolarized hot symmetric nuclear matter ($\beta = 0.0$) versus the total number density (ρ) at $T = 0, 10$ and 20 MeV .

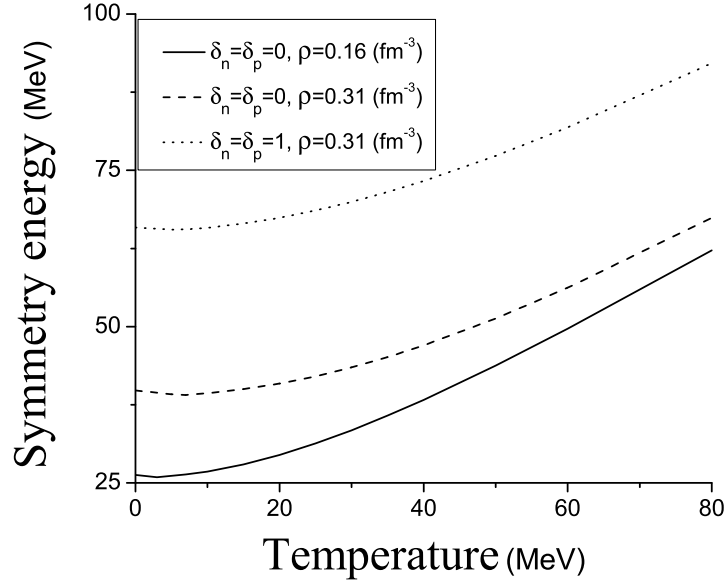


FIG. 3: The symmetry energy of the spin polarized hot asymmetric nuclear matter versus temperature for two values of the density at different polarizations.

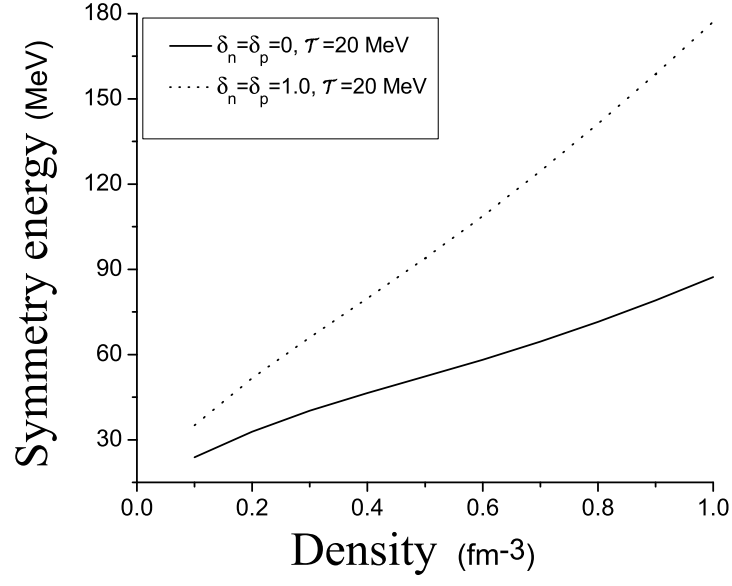


FIG. 4: The symmetry energy of spin polarized hot asymmetric nuclear matter versus density at $\mathcal{T} = 20 \text{ MeV}$ for different polarizations.

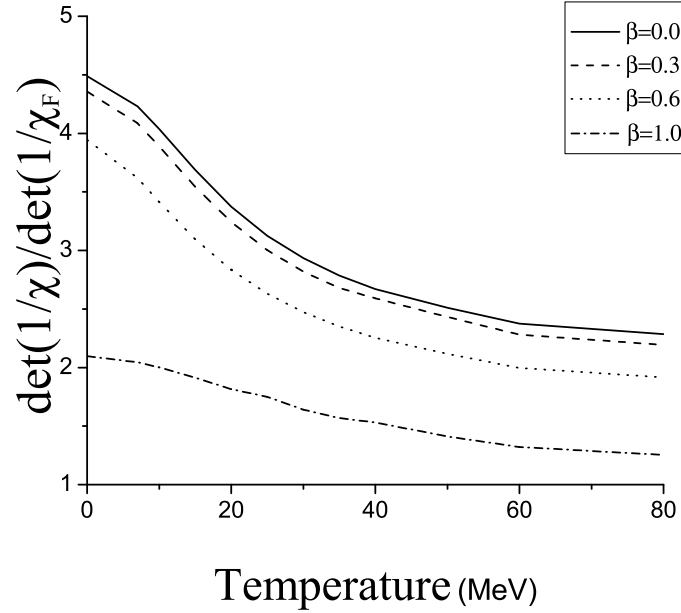


FIG. 5: The magnetic susceptibility of hot asymmetric nuclear matter versus temperature at $\rho = 0.16 \text{ fm}^{-3}$ for different values of the asymmetry parameter (β).

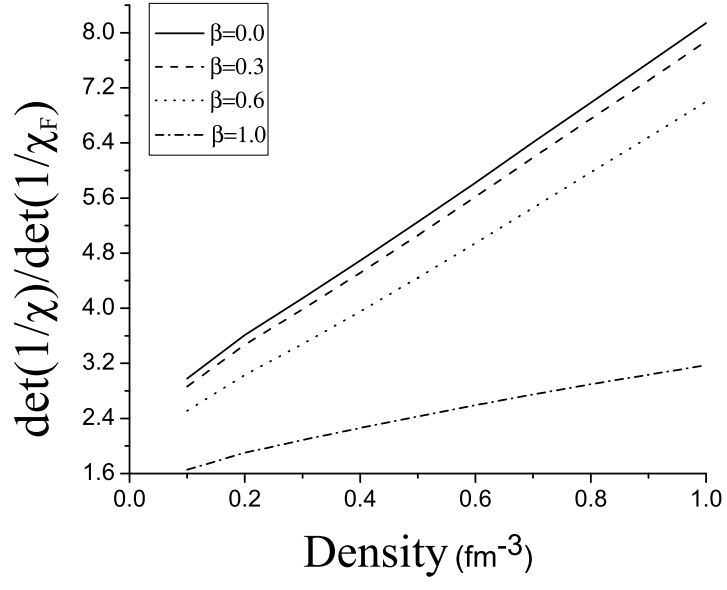


FIG. 6: The magnetic susceptibility of hot asymmetric nuclear matter versus the total number density (ρ) at $\mathcal{T} = 20$ MeV for different values of the asymmetry parameter (β).

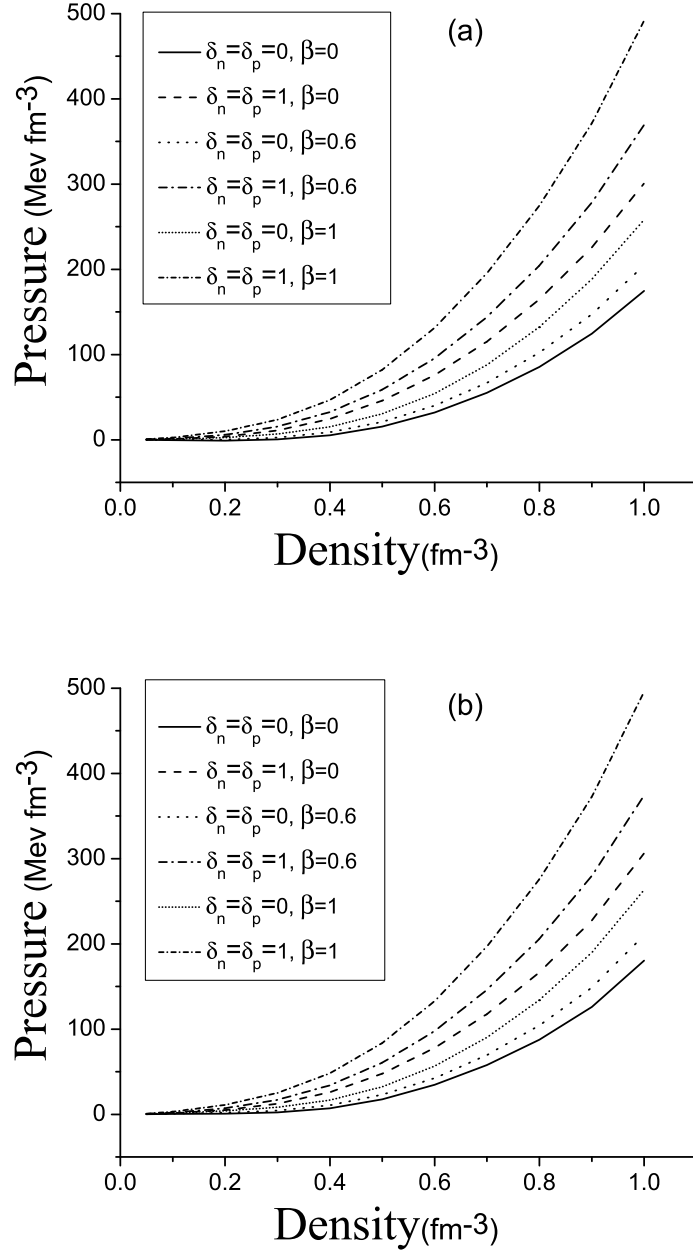


FIG. 7: The equation of state of spin polarized hot asymmetric nuclear matter for different values of the polarization and asymmetry parameter at $\mathcal{T} = 10$ MeV (a) and $\mathcal{T} = 20$ MeV (b).